IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

This is a U.S. Patent Application for:

Title: SINGLE-MODE VERTICAL CAVITY SURFACE EMITTING LASERS
AND METHODS OF MAKING THE SAME

Inventor #1: Bernhard Ulrich Koelle
Address: 350 Elan Village Lane #224, San Jose, CA 95134
Citizenship: Germany

Inventor #2: Scott W. Corzine
Address: 1354 Egret Drive, Sunnyvale, CA 94087
Citizenship: United States

Inventor #3: Laura Giovane
Address: 2147 Newhall Street # 313, Santa Clara, CA 95050
Citizenship: United States

Inventor #4: An-Nien Cheng
Address: 5983 Randleswood Ct., San Jose, CA 95129
Citizenship: Taiwan

SINGLE-MODE VERTICAL CAVITY SURFACE EMITTING LASERS AND METHODS OF MAKING THE SAME

BACKGROUND

A VCSEL is a laser device formed from an optically active semiconductor region that is sandwiched between a pair of highly reflective mirror stacks, which may be formed from layers of metallic material, dielectric material or epitaxially-grown semiconductor material. Typically, one of the mirror stacks is made less reflective than the other so that a portion of the coherent light that builds in a resonating cavity formed between the mirror stacks may be emitted preferentially from one side of the device. Typically, a VCSEL emits laser light from the top or bottom surface of the resonating cavity with a relatively small beam divergence. VCSELs may be arranged in singlets, one-dimensional or two-dimensional arrays, tested on wafer, and incorporated easily into an optical transceiver module that may be coupled to a fiber optic cable.

In general, a VCSEL may be characterized as a gain-guided VCSEL or an index-guided VCSEL. An implant VCSEL is the most common commercially available gain-guided VCSEL. An implant VCSEL includes one or more high resistance implant regions for current confinement and parasitic reduction. An oxide VCSEL, on the other hand, is the most common laterally index-guided VCSEL. An oxide VCSEL includes oxide layers (and possibly implant regions) for both current and optical confinement.

VCSELs and VCSEL arrays have been successfully developed for single-mode operation and multi-mode operation at a variety of different wavelengths (e.g., 650 nm, 850 nm, 980 nm, 1300 nm and 1550 nm).

In general, it is desirable for single-mode VCSELs to exhibit single-mode behavior within a range of specified operating conditions, while complying with other performance specifications. In general, it is desirable to increase the single-mode optical power produced by a VCSEL. In addition, it is desirable to reduce the series resistance of a VCSEL and the divergence of the output optical beam produced by the VCSEL. It also is desirable to reduce the susceptibility of a VCSEL to damage by electrostatic discharge (ESD). In some prior approaches,

both high series resistance and low ESD thresholds have been linked to small current apertures.

A high injection current is needed to generate high output power from a VCSEL. A higher injection current, however, causes the output beam to diverge through a well-known beam-steering effect that results from the interaction between the lateral modes of the VCSEL and current-induced changes in the refractive index in the wave guiding structure of the VCSEL. At low injection current, a VCSEL typically operates in the fundamental (i.e., lowest order) lateral mode, and the refractive index in the wave guiding structure remains substantially constant. At higher injection current, however, the mode structure becomes unstable due to ohmic heating and spatial hole burning effects. These changes allow higher order lateral modes to propagate with higher divergence angles, resulting in less efficient coupling between the VCSEL and the associated optical fiber used to transfer light from the VCSEL. For implant VCSELs, the mixing between different lasing modes often is detected as a kink in a graph of optical power plotted as a function of the injection current (often called the "L-I" curve) for the VCSEL.

The size of the current aperture of a VCSEL has been increased to increase the output optical power of the device. A larger current aperture also reduces the series resistance of the VCSEL. Larger current apertures, however, increase the likelihood that higher order lasing modes will propagate and mix with the fundamental mode. Extended cavity structures and optical anti-guiding structures have been introduced into the wave guiding cavities of VCSELs to suppress higher order lasing modes. Oftentimes, the introduction of such structures increases the complexity and reduces the reliability of the VCSEL manufacturing process.

SUMMARY

The invention features single-mode vertical cavity surface emitting lasers and methods of making the same.

In one aspect of the invention, a vertical cavity surface emitting laser (VCSEL) is operable to generate single-mode laser light at an operative wavelength. The VCSEL includes a light-emitting surface and a monolithic longitudinal stack structure. The longitudinal stack structure includes a first

mirror, a second mirror, and a cavity region. The first mirror has an optical reflectivity R_1 for light at the operative wavelength. The second mirror has an optical reflectivity R_2 for light at the operative wavelength, wherein R_1 and R_2 have different respective values one of which is greater than 99.9% and another of which is less than 99.7%. The cavity region is disposed between the first mirror and the second mirror and includes an active light generation region and a cavity extension region. The longitudinal stack structure further includes an ion-implanted current confinement region that is characterized by a peak longitudinal implant concentration separated from the cavity region by a longitudinal distance greater than 0.5 micrometers.

The invention also features a VCSEL array incorporating the above described VCSEL and a method of making the above-described VCSEL.

Other features and advantages of the invention will become apparent from the following description, including the drawings and the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a diagrammatic cross-sectional side view of a gain-guided VCSEL that includes an ion-implanted region defining a current aperture and a cavity region disposed between first and second mirrors.

FIG. 2 is a graph of implant concentration plotted as a function of distance from the cavity region for an exemplary implementation of the VCSEL of FIG. 1.

FIG. 3 is a diagrammatic cross-sectional side view of an alternative gain-guided VCSEL that includes a cavity extension region with a first portion adjacent to a first mirror and a second portion adjacent to a second mirror.

FIG. 4 is a graph of light optical power (LOP) and voltage (V) plotted as a function of forward injection current (current) for different implementations of the VCSEL of FIG. 1.

FIG. 5 is a graph of side-mode suppression ratio plotted as a function of bias current for an implementation of the VCSEL of FIG. 1.

DETAILED DESCRIPTION

In the following description, like reference numbers are used to identify like elements. Furthermore, the drawings are intended to illustrate major features

of exemplary embodiments in a diagrammatic manner. The drawings are not intended to depict every feature of actual embodiments nor relative dimensions of the depicted elements, and are not drawn to scale.

I.   OVERVIEW OF VCSEL STRUCTURE

5   FIG. 1 shows an embodiment of a planar gain-guided VCSEL 10 that is operable to generate single-mode laser light at an operative wavelength (e.g., a wavelength 650 nm, 850 nm, 980 nm, 1300 nm and 1550 nm). As used herein, "single-mode laser light" refers to output light of VCSEL 10 that is characterized by a wavelength spectrum with a single dominant intensity peak with a side mode

10   suppression ratio (SMSR) greater than 30 decibels (dB). The wavelength of the single dominant intensity peak is referred to herein as the "operative wavelength".

          VCSEL 10 has a monolithic stack structure extending in a longitudinal (Z) direction that includes a cavity region 12 sandwiched between a first mirror 14

15   and a second mirror 16. The monolithic stack structure is formed on a substrate 18. An optional buffer layer 17 may be grown between the substrate 18 and the monolithic stack structure. The first and second mirrors 14, 16 are formed of material layers characterized by high electrical conductivity. Cavity region 12 includes an active light generation region 19 and a cavity extension region 26.

20   The active region 19 includes one or more active layers 20 that may include, for example, one or more quantum wells or one or more quantum dots, that are sandwiched between a pair of barrier layers 22, 24. A ring-shaped ion-implanted current confinement region 28 is disposed between a light-emitting surface 30 of VCSEL 10 and the cavity region 12. The current confinement region 28

25   corresponds to a ring-shaped region of material that has been damaged by ions (i.e., protons) that have been implanted in the layers of first mirror 14. The damage caused by the implanted ions converts the implanted mirror material into a material with a high electrical resistance. The current confinement region 28 surrounds a current aperture 32 that is formed from un-implanted (and,

30   consequently, substantially undamaged) mirror material that substantially retains its original high electrical conductivity. In some implementations, the diameter of the current aperture 32 is about fifteen times the operative wavelength in free space.

A first ring-shaped electrical contact 34 is formed on the light-emitting surface 30. A second electrical contact 36 is located at the opposite end of VCSEL 10. The first and second electrical contacts 34, 36 enable VCSEL 10 to be driven by a suitable driving circuit. In operation, an operating voltage is applied across
5   electrical contacts 34, 36 to produce a current flow in VCSEL 10. In general, current flows through a central region of the VCSEL structure and lasing occurs in a central portion of cavity region 12. The aperture 32 surrounded by ion-implanted region 28 in the first mirror stack 14 laterally confines electrical carriers to the central region of the VCSEL structure. Carrier confinement results from the
10   relatively high electrical resistivity of the confinement region 28, which causes electrical current preferentially to flow through the centrally located aperture 32. The lateral electrical carrier confinement increases the density of electrical carriers within the active region and, consequently, increases the efficiency with which light is generated within the active region. It is believed that the electrical contact
15   34 acts as an optical loss guiding mechanism so that the aperture in the electrical contact 34 sets the divergence angle of the laser light emitted from VCSEL 10. In some implementations, the diameter of the aperture in electrical contact 34 is smaller than the diameter of the ion-implanted current aperture 32.

In the illustrated embodiment, each of the first and second mirrors 14, 16
20   includes a system of alternating layers of different refractive index materials that forms a distributed Bragg reflector (DBR) designed for a specified operative laser wavelength (e.g., a wavelength in the range of 650 nm to 1650 nm). For example, first and second mirror stacks 14, 16 may be formed of alternating layers of high aluminum content AlGaAs and low aluminum content AlGaAs. The layers
25   of first and second mirror stacks 14, 16 preferably have an effective optical thickness (i.e., the layer thickness multiplied by the refractive index of the layer) that is about one-quarter of the operating laser wavelength. Substrate 18 may be formed from GaAs, InP, sapphire (Al_2O_3), or InGaAs and may be undoped, doped n-type (e.g., with Si) or doped p-type (e.g., with Zn). The mirror located closest
30   to the light-emitting surface 30 is made less reflective than the other mirror so that a portion of the coherent light that builds in cavity region 12 is preferentially emitted through the light-emitting surface 30.

In the embodiments illustrated herein, first and second mirrors 14, 16 are designed so that laser light is emitted from the top surface of VCSEL 10. In other embodiments, the mirror stacks 14, 16 may be designed so that laser light is emitted from the bottom surface of substrate 18.

5   First and second barrier layers 22, 24 may be formed from materials chosen based upon the material composition of the active layers. In some implementations, active layers 20 and barrier layers 22, 24 may be formed from different respective compositions of AlInGaAs (i.e., AlInGaAs, GaAs, AlGaAs and InGaAs), InGaAsP (i.e., InGaAsP, GaAs, InGaAs, GaAsP, and GaP), GaAsSb (i.e.,

10   GaAsSb, GaAs, and GaSb), InGaAsN (i.e., InGaAsN, GaAs, InGaAs, GaAsN, and GaN), or AlInGaAsP (i.e., AlInGaAsP, AlInGaAs, AlGaAs, InGaAs, InGaAsP, GaAs, InGaAs, GaAsP, and GaP). Other quantum well layer compositions also may be used. The cavity extension region 26 is formed of a material that is substantially transparent to light at the operative wavelength and that can be formed

15   monolithically with the other layers of VCSEL 10. In some implementations, the cavity extension region 26 is formed of the same material that is used to form one of the constituent layers of the first and second mirrors 14, 16.

In some implementations, the active region 19 has an optical thickness that is substantially equal to the operative wavelength of VCSEL 10. In these

20   implementations, cavity extension region 26 has an optical thickness in the longitudinal direction (Z) that is substantially equal to an integral multiple of one-half of the operative wavelength of VCSEL 10.

VCSEL 10 may be formed by conventional epitaxial growth processes, such as metal-organic chemical vapor deposition (MOCVD) and molecular beam

25   epitaxy (MBE).

As explained in detail below, various features of VCSEL 10 are selected so that implementations of VCSEL 10 are characterized by relatively high single-mode output optical power, relatively low series resistance, and relatively smooth (non-kinky) L-I curves. In particular, the separation between the ion-implanted

30   region 28 and the cavity region 12, the reflectivity of the light-emission mirror (e.g., first mirror 14 in the embodiment of FIG. 1), and the optical thickness of the cavity extension region 26 are selected to cooperatively obtain improved VCSEL

performance with a device characterized by reduced manufacturing complexity and increased manufacturing reliability.

Implant Depth

It has been observed that reducing the depth of the implanted region (i.e., increasing the separation between the ion-implanted region 28 and the cavity region 12) increases the forward leakage current (i.e., the portion of the forward injection current that is not used to generate light) and therefore increases the lasing threshold current level. The resulting L-I curves for such VCSELs, however, have been observed to be less kinky. It is believed that this effect results from better control of the forward injection current at higher current levels. Reducing the depth of the implanted region also improves current uniformity across the cavity 12, reduces current crowding, reduces thermal lensing effects, and reduces the likelihood of implant damage extending to the active layer 20 and adversely affecting device performance.

Referring to FIGS. 1 and 2, improved VCSEL performance is achieved by positioning the ion-implanted region between the light-emitting surface 30 and the cavity region 12 at a location where the peak longitudinal implant concentration (C_P) is separated from the cavity region 12 by a longitudinal distance ΔZ_P that is greater than 0.5 micrometers (µm).

In some implementations, the ion-implanted region is positioned between the light-emitting surface 30 and the cavity region 12 at a location where the peak longitudinal implant concentration (C_P) is separated from the cavity region 12 by a longitudinal distance ΔZ_P that is greater than three times the straggle (ΔZ_S) of the ion-implanted region 28. The longitudinal straggle (ΔZ_S) is the standard deviation in the areal concentration of implanted ions about the peak lateral (in the X-Y plane) areal ion concentration. In one formulation, the longitudinal straggle may be computed using equation (1):

$$\Delta Z_S = \sqrt{\frac{1}{\varphi} \int_{-\infty}^{Z_{LE}} (Z - \Delta Z_P)^2 \cdot C(Z)dZ} \qquad (1)$$

where C(Z) is the lateral areal concentration of implanted ions (ions per unit area) and ϕ is the ion implantation dose, which is given by equation (2):

$$\varphi = \int\limits_{-\infty}^{Z_{LE}} C(Z)dZ \qquad (2)$$

Light Emission Mirror Reflectivity

It has been observed that reducing the reflectivity of the light emission mirror reduces the light generation efficiency of VCSEL 10 by increasing the

5   forward leakage current, increasing the lasing threshold current level. As explained above, however, increasing the lasing threshold current level by increasing the leakage current has been observed to improve the characteristic L-I curve for the VCSEL. In addition, it has been observed that reducing the reflectivity of the light emission mirror in this way increases the single-mode

10   output optical power.

Improved VCSEL performance is achieved by configuring the light emission mirror (e.g., first mirror 14 in VCSEL 10) to have a reflectivity ranging from preferably 99.0-99.9%, and more preferably ranging from 99.3-99.7%, for light at the operative wavelength, and configuring the non-light-emission mirror (e.g.,

15   second mirror 16 in VCSEL 10) to have a reflectivity greater than 99.9% for light at the operative wavelength.

Extended Cavity Region Thickness

Improved VCSEL performance is achieved by configuring the cavity extension region 26 to have a thickness in the longitudinal (Z) direction that is

20   greater than twice the operative wavelength. In some implementations, the optical thickness of the cavity extension region is less than about twenty times the operative wavelength.

As shown in FIG. 3, in some embodiments, the cavity extension region includes a first portion 42 that is adjacent to the first mirror 14 and second portion

25   44 that is adjacent to the second mirror 16. In other respects, the cavity extension region 42, 44 is the same as the cavity extension region 26 in the VCSEL embodiment of FIG. 1.

II.   EXEMPLARY IMPLEMENTATION OF VCSEL 10

In some exemplary implementations of VCSEL 10, the active region 19 has

30   an optical thickness in the longitudinal direction substantially equal to the operative wavelength and the cavity extension region 26 has an optical thickness

in the longitudinal direction substantially equal to an integral multiple of one-half the operative wavelength in the range of two times the operative wavelength and sixteen times the operative wavelength. The first mirror 14 is a DBR mirror stack that has twenty-one mirror layer pairs that are doped p-type and the second

5   mirror 16 is a DBR mirror stack that has forty mirror layer pairs that are doped n-type. The lasing wavelength is between 780 nm and 850 nm, with a nominal target wavelength of 840 nm. The DBR mirrors 14, 16 are composed of quarter-wave stacks of nominally $Al_{0.2}Ga_{0.8}As$ and $Al_{0.9}Ga_{0.1}As$, respectively. A highly doped contact layer and a current spreader are placed atop the first p-type DBR

10   mirror 14 for good contact and current spreading.

The implant aperture 32 is preferably less than 12 μm in diameter. The opening defined by the p-type electrical contact 34 preferably is less than 10 μm in diameter. In an embodiment in which the implant aperture is about 10 μm in diameter, the opening defined by the p-type electrical contact is about 6 μm in

15   diameter. The n-type electrical contact 34 is placed on the substrate 18. The implant energy for implanting protons to form the current confinement region 28 is 190 keV. A separate, deep implant (25 μm in diameter) is used to limit lateral leakage current through the junction.

Depending on the length of the extended cavity, single-mode lasing in DC

20   (direct current) operation (i.e., the side-mode suppression ratio (SMSR) is greater than 30 dB) is achieved for high bias currents. For example, single-mode light output at more than 2.5 mW has been observed without mode switching at an operating bias of about 9 mA and 2.5 V for a VCSEL with a cavity extension region 26 with a thickness of 10.5 times the operative wavelength and formed of a

25   material corresponding to the first layer of the second, n-type mirror stack 16.

FIG. 4 shows a graph of light optical power (LOP) and voltage (V) plotted as a function of forward injection current (current) for different implementations of the exemplary implementation of VCSEL 10. FIG. 5 shows a graph of side-mode suppression ratio plotted as a function of bias current for an

30   implementation of the VCSEL of FIG. 1.

III.   CONCLUSION

In sum, the embodiments described herein feature single-mode vertical cavity surface emitting lasers (VCSELs) that incorporate a set of features

configured to improve single-mode output optical power performance. This combination of features counter-intuitively leverages the improved current uniformity of intentionally high leakage currents and lower emission mirror reflectivity, which operate to push out the lasing current threshold, to produce VCSELs with higher single-mode output power. This allows VCSELs with larger current apertures (and consequently lower electrostatic discharge thresholds and lower series resistance) and higher single-mode output optical power to be formed.

Other embodiments are within the scope of the claims. For example,